APPLICATION NOTE

# SiC Power Schottky Diodes in Power Factor Correction Circuits

By Ranbir Singh and James Richmond

## Introduction

Electronic systems operating in the 600-1200 V range currently utilize silicon (Si) PiN diodes, which tend to store large amounts of minority carrier charge in the forward-biased state. The stored charge has to be removed by carrier recombination before the diode can be turned off. This causes long storage and turn-off times. Power devices made with Silicon Carbide (SiC) show great performance advantages as compared to those made with other semiconductors. The prime benefits of the SiC Schottky Barrier Diode (SBD) lie in its ability to switch fast (<50 ns), with almost zero reverse recovery charge, even at high junction temperature operation. The comparable Silicon PiN diodes (Si SBDs are not viable in the 600 V range because of their large on-state voltage drops) have a reverse recovery charge of 100-500 nC and take at least 100 ns to turn-off. This places a tremendous burden on other switching elements in the system in terms of the required forward safe operating area and the switching losses incurred.

In traditional off-line AC-DC power supplies used in computer and telecom applications, the AC input sees a large inductive (transformer) load which causes the power factor to be substantially lower than 1. A PFC circuit allows the AC input line to see near-unity power factor, as required by new legal requirements. The Power Factor Correction (PFC) circuits can be divided in two broad categories: Boost converter driven in (1) Discontinuous Conduction Mode (DCM) and (2) Continuous Conduction Mode (CCM). DCM circuits do not require high-speed rectifiers, but suffer from: de-rating of circuit components; instability under light load conditions; and complex EMI filtering systems. On the other hand, CCM circuits offer low RMS currents, are stable during operation under light load condition, and offer good synchronization with SMPS PWM circuits, but require an ultrafast diode. Silicon (Si) ultra fast recovery diodes have high $Q_{rr}$ (~ 100 nC), which increases significantly with di/dt, forward current and temperature. On the contrary, the $Q_{rr}$ of SiC SBDs is relatively independent of these parameters. One of the biggest applications for SiC SBDs in the near future is in the CCM power factor correction (PFC) circuit.

## SiC Schottky Diodes

*Characteristics of SiC SBDs*

600 V SiC SBDs are presently available in the 1 A, 4 A, 6 A, 10 A and 20 A ratings from Cree (www.cree.com). Figure 1 shows a typical temperature dependent forward characteristic of a 4 A / 600 V SiC SBD (CSD04060).

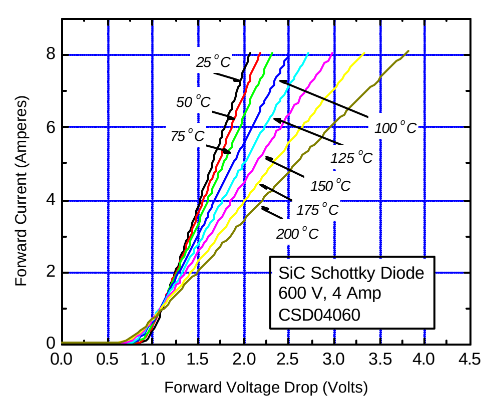



**Figure 1: The forward characteristics of a 4 A/600 V SiC SBD.**

The on-resistance increases with temperature due to the reduction in the electron mobility at elevated temperatures. The diode carries 4 A at a $V_F$ of 1.52 V at 25°C. The current reduces to approximately 2 A at the same $V_F$ at 200°C. This negative temperature coefficient of forward current allows us to parallel more than one die in a package, or many in a circuit, without any unequal current sharing issues. This behavior is unlike high voltage Si PiN diodes. Figure 2 shows the reverse characteristics of the 4 A / 600 V SBD. The typical leakage current is less than 20 µA at 600 V at 25°C which increases to 50 µA at 200°C – a very nominal increase for such a wide temperature range.

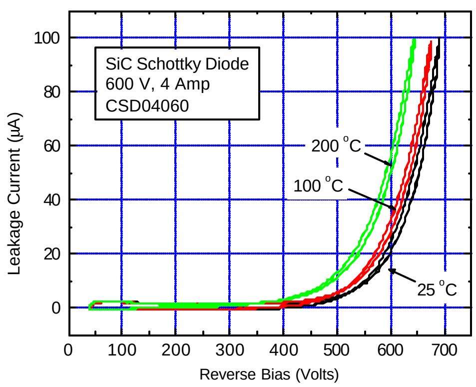



**Figure 2: The reverse characteristics of a 4 A/600 V SiC SBD.**

The devices were packaged in plastic TO-220 packages. These parts are rated for a maximum junction temperature of 175°C. For a case temperature of up to 150°C, the junction temperature remains below 175°C at full rated current.

The turn-off characteristics of the 10 A/600 V SiC SBD are compared with a Si FRED at different temperatures (Figure 3). The SiC diode, being a majority carrier device, does not have any stored minority carriers. Therefore, there is no reverse recovery current associated with the turn-off transient of the SBD. However, there is a

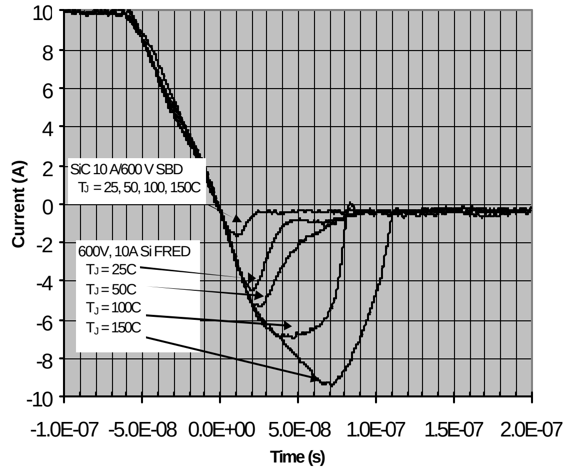



**Figure 3: Turn-off switching waveform of the 10 A / 600 V SiC SBD in comparison to Si FRED (IXYS DSEI 12-06A).**

small amount of displacement current required to charge the Schottky junction capacitance (< 2 A), which is independent of the temperature, current level and di/dt. In contrast to the SiC SBD, the Si FRED exhibits a large amount of the reverse recovery charge, which increases dramatically with temperature, on current and reverse di/dt. For example, the $Q_{rr}$ of the Si FRED is approximately 160 nC at room temperature and increases to about 450 nC at 150°C. This excessive amount of $Q_{rr}$ increases the switching losses and places a tremendous burden on the switch and diode in typical PFC applications.

## PFC Circuits

A simple CCM PFC circuit is shown in Figure 4. This circuit achieves near-unity power factor by chopping the full wave rectified input with a fast switch (MOSFET), and then stabilizing the resulting DC waveform using a capacitor. When the MOSFET is ON, it is necessary to prevent the current to flow from the output capacitor or the load through the MOSFET. Hence, when the Diode is ON, the FET is OFF, and vice versa.

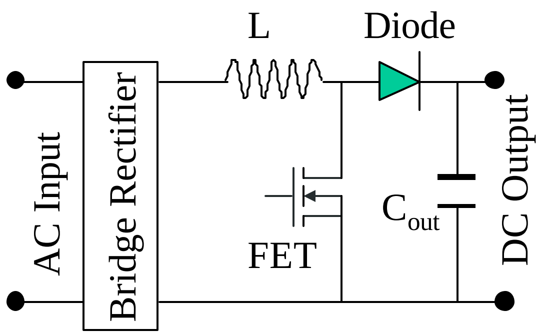



**Figure 4: A simple CCM PFC boost circuit for off-line applications.**

During the switching transient when the Diode is turning OFF and the MOSFET is turning ON, the reverse recovery current from the Diode flows into the MOSFET, in addition to the rectified input current. This results in a large inrush current into the MOSFET, necessitating its substantial de-rating as compared to the case where the Diode had no reverse recovery current. This large MOSFET represents a substantial cost in this circuit. These switching losses also limit the frequency of operation, and the efficiency of the circuit, and hence its cost, size, weight and volume. A higher frequency would allow the size of the passive components to be correspondingly smaller. Many fast silicon rectifiers also show “snappy” reverse recovery, which results in a large EMI signature, which are also unacceptable to the new European requirements. A fast rectifier with near zero reverse recovery will allow for high efficiency PFC circuits, which also comply with new legal requirements.

A SiC diode is such a rectifier. This near-zero reverse recovery SiC Schottky rectifier offers low switching losses while still showing comparable on-state performance of conventional silicon rectifiers. Due to the majority carrier transport properties of these rectifiers, they show only a capacitive current during their turn-off transient, which flows through the power MOSFET.

## High Power PFC Circuits

SiC SBDs offer substantial cost, size and efficiency benefits in higher power (>250 Watts) PFC circuits. Such circuits require the use of passive or active snubber circuit when operated even with ultrafast Si p-i-n rectifiers in order to negate its reverse recovery charge. SiC SBDs are expected to eliminate the requirement for these snubber circuit components, as well as a severely de-rated MOSFET, while still offering a higher efficiency.

A 390 Watt power supply with passive snubber circuits was used for evaluation of 600 V / 4 A SiC SBDs (CSD04060). The power supply was composed of two sections: a PFC stage, which takes in 85 V – 265 V as AC input voltage and boosts it to

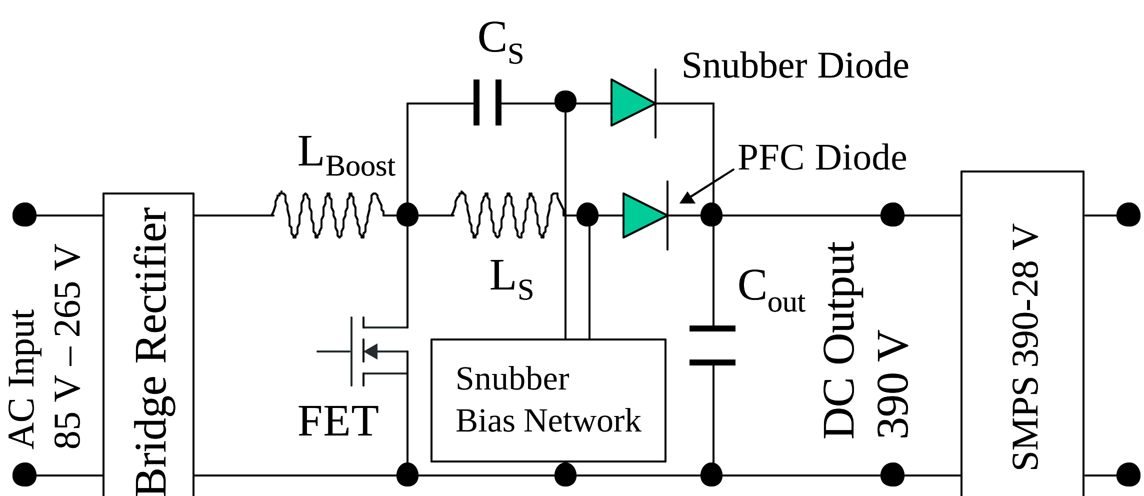



**Figure 5: High Power PFC circuit with snubber components.**

390 V DC output; a step down SMPS, which steps down the DC voltage from 390 V to 28 V output.

The schematic diagram of the PFC stage of this power supply is shown in Figure 5. This PFC stage uses TWO 500 V / 14 A, MOSFETs (IRFP450) in parallel (not shown) and a dual 600 V / 4 A MURH860CT as PFC diode, and Snubber diode. The snubber components re-direct the reverse recovery charge from the PFC diode to an alternative bias network. A snubber inductor ($L_S$) in series with the PFC diode and a snubber capacitor ($C_S$) in series with a Snubber diode provide the necessary lag for the re-direction of this reverse recovery current away from the two power MOSFETs during its turn-on transient. Switching waveforms were taken under full load condition, i.e. a 2 Ω load for a 28 V output voltage. The operating frequency was 95 kHz, and all measurements were conducted under room temperature ambient.

*Switching waveforms using Si Diodes*

The measured current and voltage switching waveform on the Si PFC diode are shown in Figure 6 (a). These measurements were taken under full load condition, and an input voltage of 85 V AC. This condition represents the highest duty cycle for the diode, with the snubber. A peak reverse recovery current of 1.8 A is observed when this diode turned off at a reverse di/dt of 200 A/µsec. A turn-on dv/dt of 3.5 kV/µsec was used when the diode transitions from OFF-state to ON-state. The switching waveforms on the Si snubber diode used in conjunction with with main PFC diode are shown in Figure 6 (b). It can be seen that this snubber diode does not contribute any reverse recovery current that needs to flow through the MOSFET because it is not carrying any forward current during the PFC diode switching transient. This diode provides a small

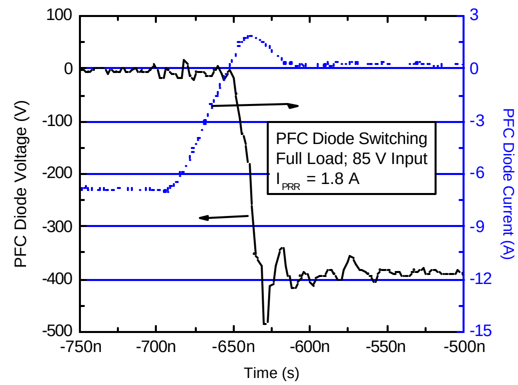



**Figure 6: (a) Si PFC Diode turn-off characteristics w/snubber.**

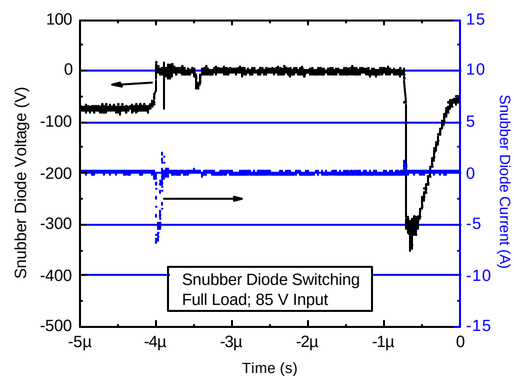



**Figure 6 (b) Snubber diode current and voltage switching waveforms.**

voltage transient to the PFC diode, which prevents it from turning off too fast.

Measurements were also performed on both MOSFETs (in parallel) in the PFC circuit. It was found that the current sharing was fairly uniform between the two MOSFETs. The MOSFET voltage and current switching waveforms under full load condition at an 85 V AC input is shown in Figure 7. This circuit uses a Si PFC diode in addition to the snubber circuit. A turn-on di/dt of 81 A/µsec was measured and the MOSFET turns on with a total current of 5.96 A, which decays to 3.44 A within a microsecond. This represents an excess current of 2.52 A during turn on of the MOSFET.

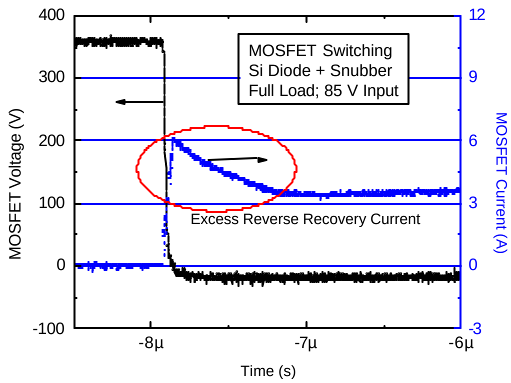



**Figure 7: MOSFET Current and Voltage turn-on waveforms for the case with Si diodes and Snubber network.**

In order to ascertain the effect of snubber network on the MOSFET and PFC diode switching, the snubber network was removed from the PFC circuit. The measured MOSFET current without a snubber network is shown in Figure 8. The peak current due to diode reverse recovery increases from 1.8 A with the Snubber network to 6.5 A without the

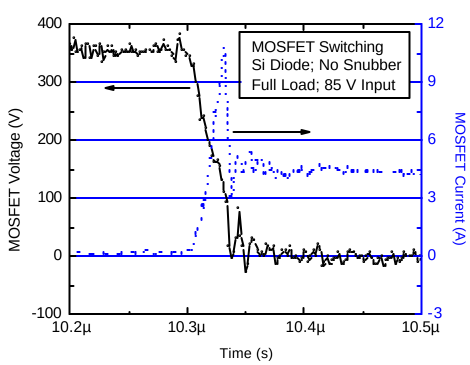



**Figure 8: MOSFET Switching waveform without Snubber network.**

snubber network. This obviously stresses the MOSFET excessively, and may lead to an excessive thermal load to the entire circuit assembly.

*Switching waveforms using SiC Diodes*

After these measurements were completed using Si diodes, the PFC diode was replaced with a SiC SBD (CSD04060), and all components of the snubber network: including snubber inductor, capacitor and the bias network; were removed, and measurements were repeated. The measured current and voltage switching waveform on the Si PFC diode are shown in Figure 9 (a). This diode turned off at a reverse di/dt of 567 A/µsec. A turn-on dv/dt of 2.7 kV/µsec was used when the diode transitions from OFF-state to ON-state.

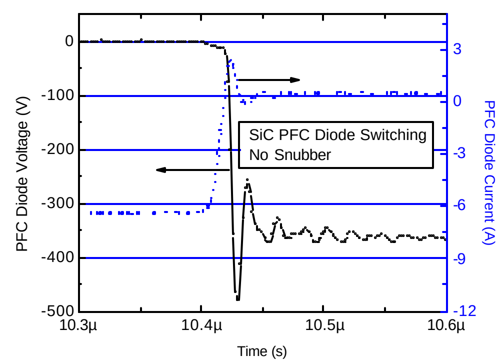



**Figure 9: (a) SiC PFC diode turn-off waveforms under full load condition and an input voltage of 85 V AC.**

The MOSFET voltage and current switching waveforms under full load condition at an 85 V AC input is shown in Figure 9 (b). This measurement was taken with SiC PFC diode, and no snubber circuit. A turn-on di/dt of 362 A/µsec was measured and the MOSFET turns on at near-nominal current level.

*Switching waveforms using SiC Diodes with SINGLE FET*

Since SiC diodes offer no reverse recovery, it may be possible to reduce the size of the MOSFETs used in the circuit, thereby saving cost, weight and size of the

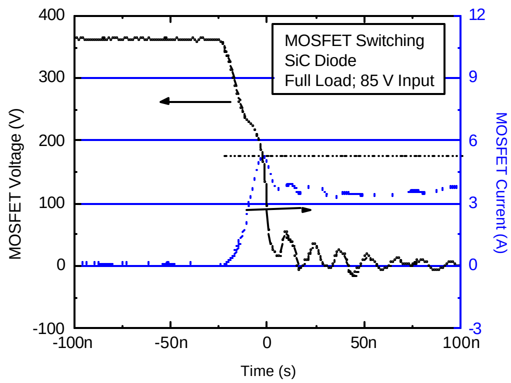



**Figure 9 (b) MOSFET current and voltage turn-on waveforms under full load condition using SiC PFC diode.**

circuit even further. This is because MOSFETs used in PFC circuits are severely de-rated due to the additional switching losses created by the reverse recovery current that flow through them during turn-on transients. As mentioned earlier, in this circuit, two MOSFETs were used in parallel in order to achieve this de-rating. After the measurements presented above were completed, a MOSFET was removed, and the circuit was operated with the SiC Schottky diode without any snubber circuit.

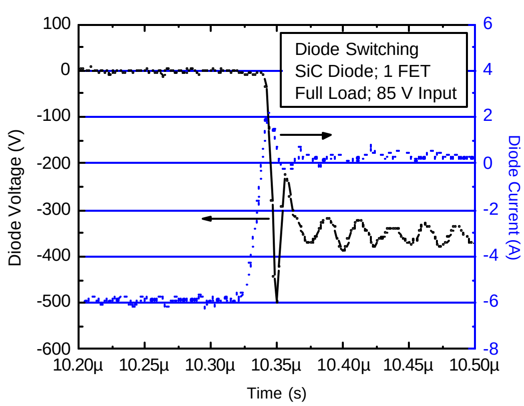
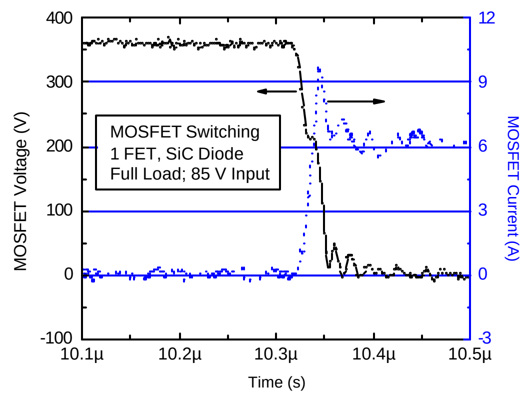



**Figure 10: (a) SiC PFC diode switching waveforms with a single MOSFET (one MOSFET removed from previous circuit) under full load condition and an input voltage of 85 V AC.**

The measured current and voltage switching waveform on the Si PFC diode are shown in Figure 10 (a).

This diode turned off at a reverse di/dt of 510 A/µsec. A turn-on dv/dt of 1.9 kV/µsec was used when the diode transitions from OFF-state to ON-state. The MOSFET voltage and current switching waveforms under full load condition at an 85 V AC input is shown in Figure 10 (b).




**(b) Single MOSFET current and voltage switching waveforms under full load condition using SiC PFC diode.**

## Efficiency and Temperature Measurements

In the test circuit, it was difficult to separate the efficiency of the PFC circuit and the next stage, which was the voltage step-down. The efficiency numbers reported here include the efficiency of the PFC stage as well as the SMPS voltage step-down stage of the power supply. Hence, the impact of SiC on the PFC stage circuit efficiency is somewhat under-estimated in these measurements Figure 11 shows the comparison of the measured efficiency of the entire power supply between Si and SiC diode.

The load was varied between 10 % (20 Ω) to 100 % (2 Ω) for its 28 V output, in 10%

increments. As mentioned earlier, in case of Si diode, the entire snubber network was included in the measurement, while in the case of SiC diode, it was removed. The case where only a single MOSFET was used is also plotted in this figure. As in most PFC circuits, the efficiency of the circuit increases as the load is increased from 10 % to 100 %.

The measurements at 85 V input voltage are presented, which represents the highest stress for the active components in the circuit. At 10 % load, the circuit efficiency increases from 51.4 % for the Si diode case to 57.5 % for SiC diode with 2 FETs, and increases further to 58.5 % for the case of single FET. At 100% load condition, the total efficiency improves from 78.9 % for the Si diode case to 81.77 % for the case of SiC diode with 2 FET; which decreases to 80.7 % for the case with a single FET. The slightly higher on-state losses in SiC Schottky diode results in the relatively smaller gain in the overall circuit efficiency under full load operating condition. In general, the efficiency of the circuit maintains a more uniform profile with a SiC PFC diode as compared to the traditional design using Si diodes.

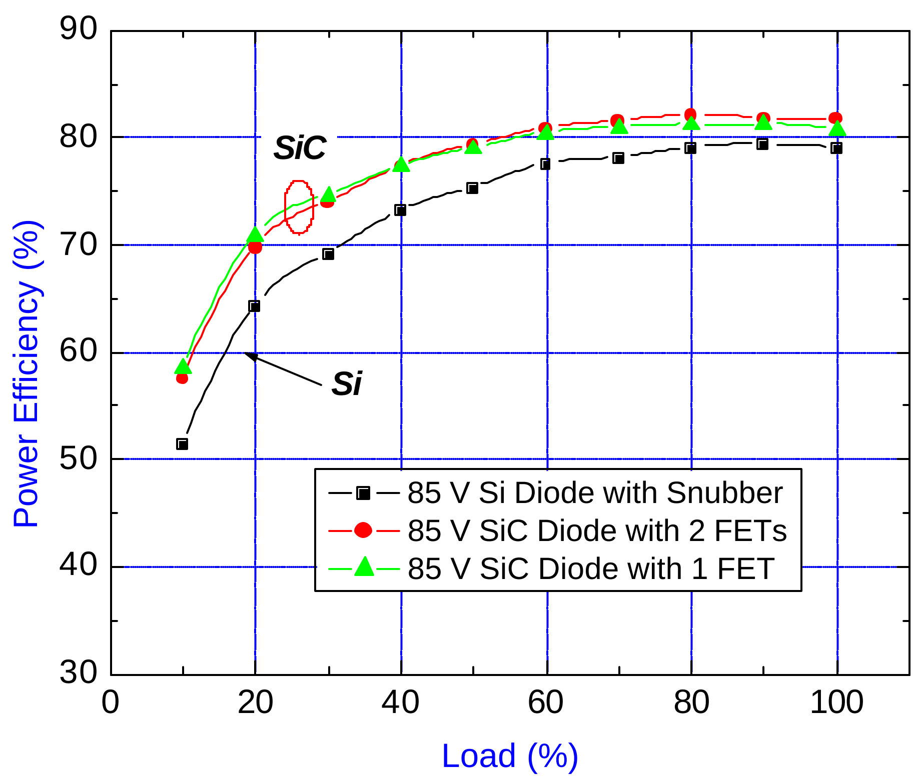



**Figure 11: Efficiency comparison of PFC circuit with Si and SiC diodes. The efficiency of the circuit with single FET remains better than that with two FETs.**

Figure 12 shows the measured MOSFET case temperature as a function of time after initial power up. Initially, the devices were in thermal equilibrium at room temperature. This measurement was done when full load operating condition was impressed on this circuit. These measurements were taken under two extreme input voltages – 85 V and 250 V. Since a higher duty cycle is used in the case of 85 V input voltage, the MOSFET sees a higher reverse recovery current causing it to have a higher case temperature. For 250 V input voltage, the MOSFET case temperature decreases from a steady state temperature of 35.7 °C when a Si PFC diode is used to 30.2 °C when a SiC PFC diode is introduced for the case with 2 FETs. When a FET was removed the case temperature on the single FET was only 32.5 °C, which is an improvement over the case with Si diode, For the 85 V input voltage, the MOSFET case temperature decreases from a steady state temperature of 45.5 °C to 42.5 °C when the SiC PFC diode is introduced for the case of 2 FETs. When one FET was removed, its temperature stabilizes at 47.6 °C, a small increase as compared to the original case with Si diode.

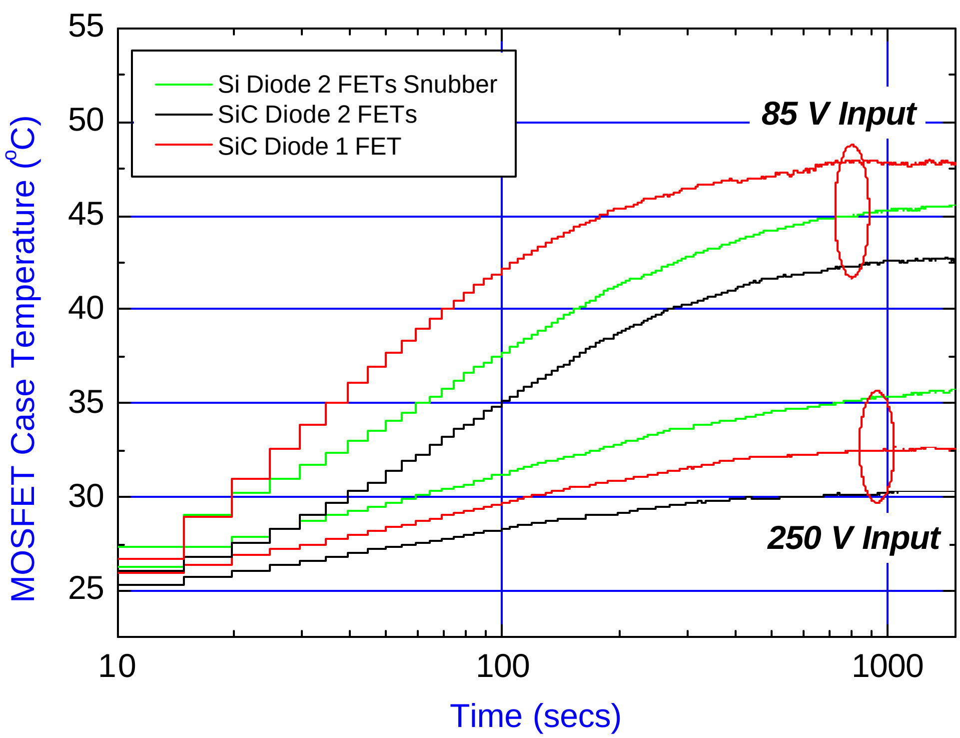



**Figure 12: MOSFET case temperature comparison for the following cases at 85 V and 250 V input: Si diode with 2 FETs, SiC diode with 2 FETs and SiC diode with single FET.**

## Conclusions

The realization of the impact of SiC SBDs on the circuit efficiency and MOSFET case temperature is of great importance to a PFC circuit designer. Based on measurements presented above, the most significant advantages offered by SiC Schottky diodes vis-à-vis Si PiN diodes in a PFC circuit are: higher circuit efficiency; lower FET case temperature; and a significant reduction in the number of circuit components, due to the elimination of the snubber inductors, capacitors and networks. These advantages can very effectively be harnessed for lowering the cost of the circuit. For a given efficiency, a higher frequency of operation of the circuit can result in smaller (and hence cheaper) inductors and MOSFETs, which are the typically the most expensive components in the PFC circuit. For an identical case temperature, a smaller and cheaper MOSFET and heat sinks can be used in the circuit. Another simple circuit modification to lower the total circuit losses involves reducing the gate resistance of the MOSFET. A higher gate resistor is used in typical PFC circuit in order to limit the di/dt in the Si PiN diode, which might result in excessive reverse recovery current, and EMI emissions. Since SiC Schottky diodes can operate under very high di/dt, a smaller MOSFET gate resistance can be utilized, further reducing MOSFET turn-on losses. Such a modification will also result in lowering the MOSFET turn-OFF losses, which showed little change with direct replacement of SiC Schottky diode with Si PiN diode in the PFC circuit described above.

The resulting circuit is much more simplified, and reduces manufacturing costs, design errors, as well as fewer components that emit and absorb harmful EMI. Overall, this can also result in improved circuit reliability.

Cree, Inc.
Power Products
4600 Silicon Drive
Durham, NC  27703 • USA
tel: 919-313-5300
fax: 919-313-5451
www.cree.com